

UNIVERSITY OF TECHNOLOGY, SYDNEY

DOCTORAL THESIS

**Investigation into the Effects of
Electron-Beam Irradiation on III-Nitride
Based LED Devices**

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*A thesis submitted in fulfilment of the requirements
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School of Physics and Advanced Materials

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Declaration of Authorship

I, Mark N. LOCKREY, declare that this thesis titled, ‘Investigation into the Effects of Electron-Beam Irradiation on III-Nitride Based LED Devices’ and the work presented in it are my own. I confirm that:

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- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Date:

*Dedicated to by beautiful wife, Emma Konnaris.
Without her love and support, this thesis would not be possible.*

“The first principle is that you must not fool yourself — and you are the easiest person to fool.”

Richard Feynman

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UNIVERSITY OF TECHNOLOGY, SYDNEY

Abstract

Science

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Doctor of Philosophy

Investigation into the Effects of Electron-Beam Irradiation on III-Nitride Based LED Devices

by Mark N. LOCKREY

The effects of low-energy electron irradiation (LEEBI) on the emission from InGaN/GaN multi quantum wells (MQW) LED devices have been systematically investigated using temperature-, power- and depth-resolved cathodoluminescence (CL) studies. In this work a dedicated CL system was developed to facilitate CL spectral spatial imaging as well as CL spectral time-resolved imaging over a broad temperature range from 10 K to 750 K. LEEBI of InGaN/GaN MQWs has been previously described in the literature reporting effects such as formation of a new blue-shifted emission band from the as-fabricated MQW emission as well as both enhancement and quenching of the MQW emission. However, no clear explanation of the LEEBI induced modification of on the optical emission of MQW LED structures have been given up to now.

It has been established in this work that LEEBI of $\text{In}_{0.35}\text{Ga}_{0.65}\text{N}/\text{GaN}$ LED structures with an as-fabricated optical emission at 2.62 eV at 300 K can produce an enhancement of the electroluminescence by over 2x. It was determined that this improvement is stable up to temperatures of 150 °C. Longer LEEBI irradiation quenched the 2.62 eV peak and produce a different emission peak at 2.82 eV. Depth-resolved CL revealed that this new emission peak originates from the same depth as the MQW structure. These studies also confirmed that the LEEBI modification mechanism involves the electro-migration of H released from Mg-H complexes in the p-type capping layer that first passivates non-radiative recombination centres in the MQW increasing its light output and subsequently reacts with In within the MQW decreasing the localisation energy.

List of Publications

Journal Articles

D.J. Sprouster, S. Ruffella, J.E. Bradby, J.S. Williams, M.N. Lockrey, M.R. Phillips, R.C. Majora and O.L. Warren, *Structural characterization of B-doped diamond nanoindentation tips*, Journal of Materials Research, 26, 3051-3057 (2011)

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M.N. Lockrey, M. Huang, C. Ton That and M.R. Phillips, *Investigating the Origin of the GL Band in ZnO Nanowires Using Temperature Resolved Cathodoluminescence*, Australian Microbeam Analysis Society Symposium (AMAS XII), Sydney Australia February 2013

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M.N. Lockrey, M. Wintrebert-Fouquet, M.R. Phillips, *Modification of InGaN/GaN MQW LED devices by High Current Injection*, International Workshop on Nitride Semiconductors, Sapporo, Japan, October, 2012

M.R. Phillips, T.J. Manning, C. Nenstiel, M. Hoffmann, M. Wintrebert-Fouquet, M.N. Lockrey and A. Hoffmann, *Cathodoluminescence Studies of Electron Beam Irradiated*

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M.R. Phillips, M.N. Lockrey, C. Ton-That and M. Huang, *Cathodoluminescence Studies of ZnO from 300K to 800K*, 7th International Workshop on Zinc Oxide and Related Materials, 11-14th September, 2012, Nice France

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M.R. Phillips, M.N. Lockrey and Cuong Ton-That, *Applications of cathodoluminescence spectrum imaging: InGaN/GaN MQW emission stability and deformation mechanisms in ZnO*, 2nd International Congress in Advances in Applied Physics and Materials Science, 26 to 29 April 2012 Antalya, Turkey

Liangchen Zhu, M.N. Lockrey, Cuong Ton-That and M.R. Phillips, *Growth and optical properties of N-doped ZnO nanowires*, Conference Proceedings APMC 10 / ICONN 2012 / ACMM 22, 6-9 Feb., 2012, Perth, Western Australia

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M.N. Lockrey, M.R. Phillips, C. Peng and L. Bi, *Characterisation of InGaN/GaN nanowires using cathodoluminescence*, IUMAS-V/ALC11, Seoul Olympic Park, Seoul, Korea, 22-27 May 2011

M.R. Phillips, T.J. Manning, C. Nenstiel, T. Hardy, M.N. Lockrey, C. Ton-That and A. Hoffmann, *In-Situ Cathodoluminescence Studies of the Thermal Stability of Hydrogen in p-type Magnesium Doped Gallium Nitride*, Microscopy and Microanalysis 2011, Nashville, TN, USA, 7-11 August 2011

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M.R. Phillips, T.J. Manning, C. Nenstiel, T. Hardy, M.N. Lockrey, C. Ton-That and A. Hoffmann, *In-Situ Cathodoluminescence Studies of the Thermal Stability of Hydrogen in p-type Magnesium Doped Gallium Nitride*, Microscopy and Microanalysis, 7-11 Aug 2011, Nashville, Tennessee

M.N. Lockrey and M.R. Phillips, *Application of Spectral Mapping to the Characterisation of InGaN/GaN Quantum Well Devices*, Australian Microbeam Analysis Society XI Symposium, 7-11 February 2011, Canberra

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Awards

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Abbreviations

AR	Anti-Reflecting
BL	Blue Luminescence
BSE	Back Scattered Electron
CB	Conduction Band
CCD	Charged-Coupled Device
CL	Cathodoluminescence
DAP	Donor-Acceptor Pair
EBIC	Electron Beam Induced Current
EL	Electroluminescence
ESEM	Environmental Scanning Electron Microscope
FIB	Focused Ion Beam
FWHM	Full Width at Half Maximum
HV	High Voltage
HVPE	Hydride Vapour Phase Epitaxy
IDL	Irradiation Defect Luminescence
LEEBI	Low-Energy Electron-Beam Irradiation
LO	Longitudinal Optical
Mg:BL	Magnesium Blue Luminescence
MOCVD	Metal-Organic Chemical Vapour Deposition
MQW	Multi-Quantum Well
N.A.	Numerical Aperture
NBE	Near Band Edge
PA3	Photo Amplifier 3
PMT	Photomultiplier Tube
PL	Photoluminescence

QCSE	Quantum Confined Stark Effect
QD	Quantum Dot
QDS	Quantum Dot Solid
QW	Quantum Well
RTA	Rapid Thermal Annealing
SE	Secondary Electron
SEE	Secondary Electron Emission
SEM	Scanning Electron Microscope
TEM	Transmission Electron Microscope
UV	Ultraviolet
VB	Valance Band
VIS	Visible
YL	Yellow Luminescence